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Dr. Herschel S. Pilloff
Office of Naval Research
Physics Division (Code 1112LO)
800 North Quincy Street
Arlington, Virginia 22217-5000

Dear Hersch,

This letter constitutes the final report of work carried out under ONR Grant No. N00014-91-J-1167 (R&T No. 4124112-05) at the University of Southern California during the period 1990 December 1 to 1992 November 30. The grant, originally for three years, was terminated after two years due to my move to the University of New Mexico. It has been replaced by a new grant at New Mexico (Grant No. N00014-93-1-0116), which began 1992 December 1.

During the grant period four people were associated with me at USC. Alistair *Lane* continued as a full-time postdoc through 1991 February 28; he returned to USC on a part-time basis as of 1992 January 1, to complete work initiated earlier. Rüdiger *Schack* joined my group on 1991 November 1 as a post-doctoral Visiting Scientist. *Schack*'s background is in quantum optics (he completed his Ph.D. under Axel Schenzle in München), but he is supported entirely by a German fellowship and he has worked mainly on topics not directly related to this grant. Chang *Zhu*, USC graduate student, completed his Ph.D. in Physics in 1992 May, and Shang *Song*, USC graduate student, continued work toward a Ph.D. in Physics.

Research during the grant period was concentrated in the following areas:

• *Caves* and Peter Drummond of the University of Queensland continued work on quantum limits to communication rates. A paper originally submitted to *Physical Review A* was extensively revised and resubmitted as a review article to *Reviews of Modern Physics* (publication 7). This paper integrates the communication theorist's description of a communication channel with the physical description and thus provides physicists with an entry into communications theory. The paper has two consistent themes: (i) the quantum nature of light enforces a limit on the capacity of a wideband communications channel; (ii) it is always optimal, given a constraint on available power, to send about one photon in each field mode, which carries about one bit of information. The first theme is illustrated by examples that lead to the first general quantum-mechanical proof of the wideband capacity limit. The second theme emerges from the same examples and is illustrated further by consideration of generalized channels that use many transverse field modes. There has been an initial refereeing at *Reviews of Modern Physics*. After initial disagreement, *Caves* and Drummond have agreed how best to revise the paper, and it should be re-submitted soon. The editor has indicated that he will accept a revised paper. A short description of some of the results appeared in the proceedings of the NATO Advanced Research Workshop on Quantum Measurements in Optics (publication 4).

• *Song* and *Caves* initiated a detailed investigation of quantum limitations on phase measurements made by high-precision interferometry. Their analysis presently includes a realistic model of losses in the optical elements, quantum feedback to maintain the interferometer at its operating point, and the use of squeezed light. Still to be included is light recycling. Ronald Drever of Caltech has agreed to collaborate, so that the analysis can proceed to the most sophisticated forms of recycling and to the modulation schemes needed to implement them. This work has not as yet produced any publications, but it will constitute *Song*'s Ph.D. thesis.

• *Lane*, Braunstein, and *Caves* completed their investigation of Shapiro-Shepard-Wong (SSW) phase measurements. They concluded from extensive numerical work, together with analytical results, that SSW measurements do not achieve the sensitivity claimed by SSW, nor do they achieve even the benchmark sensitivity of squeezed-state interferometry, although they do much better than the authors would have guessed when they started their work. This work has been written up in two papers, a short one that has appeared in *Physical Review Letters* (publication 5) and a very long (30 pages) one that has been accepted for publication in *Physical Review A* (publication 6). Although this work is focused narrowly on SSW phase measurements, the techniques developed for the analysis serve as the basis for a general attack on the question of the ultimate phase sensitivity permitted by quantum mechanics.

• Braunstein and *Caves* initiated work on the geometry of Hilbert space and its relation to high-precision measurements. The natural distance between quantum states in Hilbert space is the Hilbert-space angle defined by the quantum-mechanical overlap of the states. Braunstein and *Caves* took Wootters's notion of statistical distance between probability distributions, generalized it to quantum mechanics, and showed that it is the same as the natural distance measure. The proof required combining the Fisher information of classical estimation theory with the general description of measurements in quantum mechanics. Moreover, Braunstein and *Caves* related the distance along a curve in Hilbert space to the variance of the "conjugate" operator that generates the curve and thus found Mandelstam-Tamm-type uncertainty principles for energy and time and for photon number and phase. This work was reported in an invited talk at the 1992 QELS and is now being written up for publication.

• Gerard Milburn of the University of Queensland, Braunstein, and *Caves* applied the Braunstein-*Caves* uncertainty principles to the generators of the Poincaré group in relativistic quantum mechanics. They are able to derive rigorous uncertainty principles for energy and time, 3-momentum and position, center-of-energy position and boost velocity, and angular momentum and angle. These new uncertainty principles avoid entirely the standard questions about the operator status of time, position, and angle in relativistic quantum mechanics. Milburn has drafted a short publication describing these uncertainty principles.

During the grant period *Caves* was an invited speaker at the Workshop on Squeezed States and Uncertainty Relations, held at the University of Maryland during 1991 March 28–30, where he reported preliminary results on the investigation of SSW phase measurements; *Caves* attended the Santa Fe Workshop on the Foundations of Quantum Mechanics, held during 1991 May 27–31; and *Caves* was an invited speaker at the 1992 Conference on Quantum Electronics and Laser Science, held in An...eim, California during 1992 May 10–14, where he discussed precision measurements and the geometry of Hilbert space. Drummond attended the NATO Advanced Research Workshop on Quantum Measurements in Optics, held in Cortina, Italy, during 1991 January 21–25, where he reported on his and *Caves*'s work on communication rates. Braunstein attended the 1991 Conference on Quantum Electronics and Laser Science, held in Baltimore during 1991 May 13–17, where he reported on phase-measurement work and earlier work on the positive P

representation, both carried out with support from this grant.

Sincerely,

Carlton M. Caves

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Publications published

1. C. Zhu and C. M. Caves, "Photocount distributions for continuous-wave squeezed light," *Physical Review A* **42**, 6794–6804 (1990).
2. S. L. Braunstein, C. M. Caves, and G. J. Milburn, "Interpretation for a positive *P* representation," *Physical Review A* **43**, 1153–1159 (1991).
3. C. M. Caves, C. Zhu, G. J. Milburn, and W. Schleich, "Photon statistics of two-mode squeezed states and interference in four-dimensional phase space," *Physical Review A* **43**, 3854–3861 (1991).
4. P. D. Drummond and C. M. Caves, "Wideband quantum communication: A new frontier?" in *Quantum Measurements in Optics*, edited by P. Tombesi and D. F. Walls (Plenum, New York, 1992), pages 279–294.
5. S. L. Braunstein, A. S. Lane, and C. M. Caves, "Maximum-likelihood analysis of multiple quantum phase measurements," *Physical Review Letters* **69**, 2153–2156 (1992).

Publications submitted

6. A. S. Lane, S. L. Braunstein, and C. M. Caves, "Maximum-likelihood statistics of multiple quantum phase measurements," *Physical Review A* **47**, xxxx-xxxx (1993).
7. C. M. Caves and P. D. Drummond, "Quantum limits on communication rates," submitted to *Reviews of Modern Physics*.